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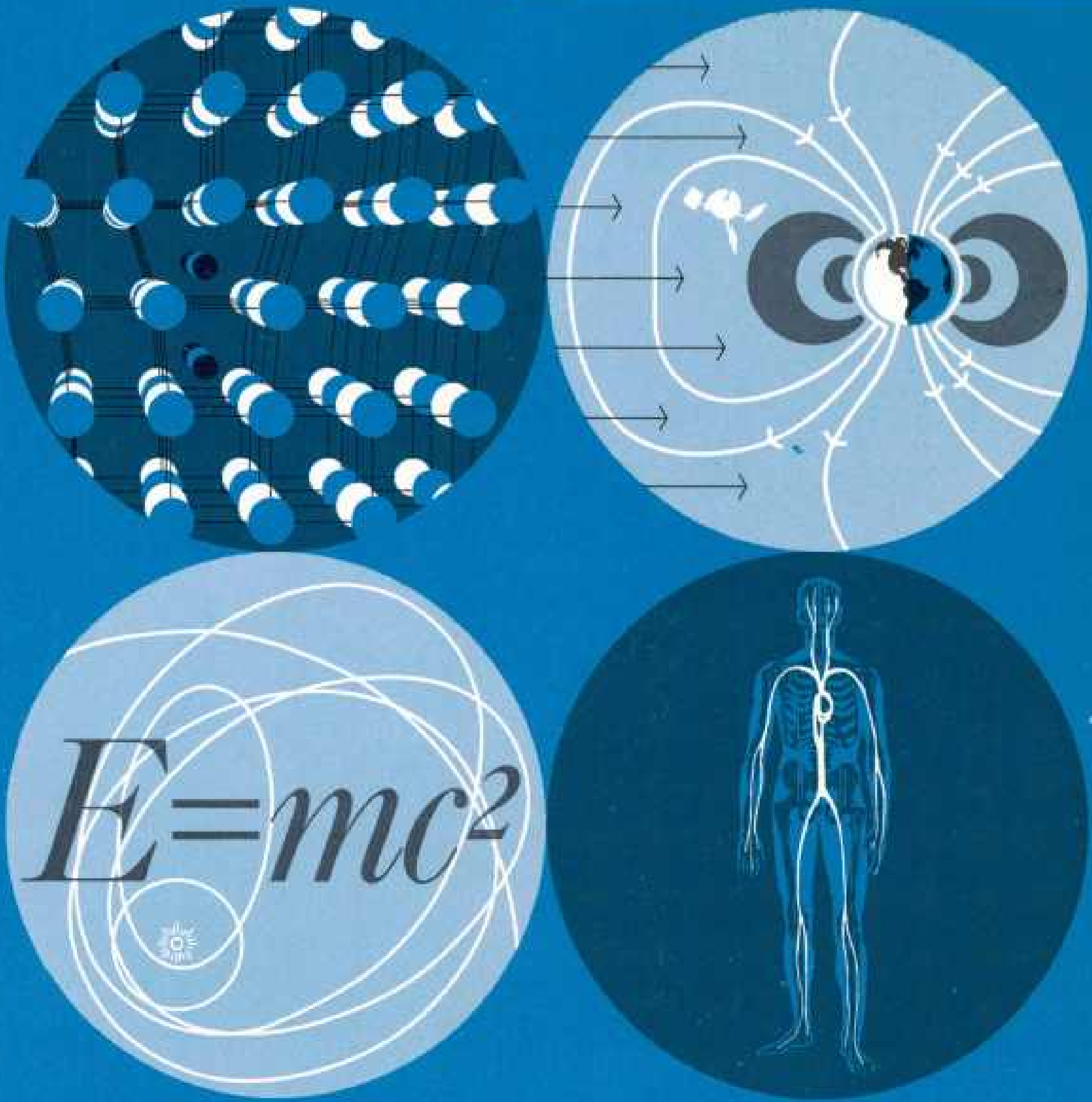

LIDAR INVESTIGATIONS OF THE SPATIAL DISTRIBUTION AND SIZES OF DROPLETS IN SPRAY PLUMES FROM OCEAN WAVES

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CREDIT

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ABSTRACT

Use of a pulsed ruby laser to map the three-dimensional development of spray plumes generated by wave action on an isolated rock at Reef Point, near Laguna Beach, California, proved the feasibility of this technique for observing spray diffusion. Observations of plume diffusion under varying conditions of sea breeze and sea state over the 200m path from the reef to the shore showed plume height to be less than would be predicted by turbulent diffusion theory for smoke clouds in thermal equilibrium with the environment. The small vertical development is attributed to the strong thermal inversions which existed over the water when the investigation was conducted, and to settling of the larger spray droplets. Evaporative cooling of the plume may also limit vertical diffusion. The experimental procedure consisted of taking several shots at each laser altitude and azimuth setting to determine the mean plume envelope, and recording holograms of spray near the breaking waves and farther downwind to monitor the evaporation of the droplets. A better understanding of the generation of giant salt nuclei, so important in warm cloud rain, might be obtained by applying this lidar technique in the tropics.

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INTRODUCTION

It is difficult to obtain data on the sizes, spatial distribution, and diffusion of sea spray near the ocean surface. Monahan (1968) has obtained direct photographs of spray particles from rafts in the open ocean; Mason (1957) and others have used impactors or other direct sampling methods to study droplets and condensation nuclei. The laser offers several advantages for obtaining new data on sea spray, since it can use the same transmitter both for monitoring macroscopic particle distributions and for making microscopic studies of individual droplets.

CONDITIONS OF THE EXPERIMENT

To study droplet sizes and spray diffusion over the open ocean, it would be ideal to have a point source of white water. The closest approximation to this ideal is an isolated rock on which waves are continually breaking. A survey of the local Southern California coastline revealed such a rock off Reef Point, northwest of Laguna Beach, California. The rock is 200m offshore, and the usual sea breeze drifts the spray plume at right angles to a low bluff 500m distant which overlooks the reef. Figure 1 is a photograph of the reef showing the breaking waves. The bluff is accessible from the Coast Highway; and for most of the tests, the lidar van was driven

Figure 1. Waves breaking at Reef Point, California

onto the bluff, although the beach level can also be reached by road, if necessary. Experiments were performed from September 1967 through March 1968 under varying meteorological conditions of wind and sea state.

The lidar used has been described in detail by Ageno (1968). The output from the Q-switched ruby laser is collimated into a 0.1 mr beam. This beam expands to a width of only 5 cm at the spray plume so that measurements may be made very close to the water surface. The 50 MHz electronic bandwidth of the photometer receiver gives a range resolution of better than 2m.

OBSERVATIONS OF SPRAY PLUMES

Except for occasional violent splashing on the reef, which gave rise to visible spindrift, the sea spray plume drifting downwind was invisible to the unaided eye. Figure 2 shows the return from a plume 46m downwind from the reef. Time progresses from left to right, with each centimeter on the reticle representing one μsec. The sharp spike return past the plume represents beam impingement on the water surface. This is the echo from spray at a height 0.5m above the surface from the bluff site.

The strength of the return signal depends strongly on the type of wave action on the rock. On days with an extremely calm surface and little wind, the receiver gain had to be increased to give a reliable amplitude, but under most conditions with the wind speed above 1m sec^{-1}, sufficient spray was carried to make the returns readily detectable.

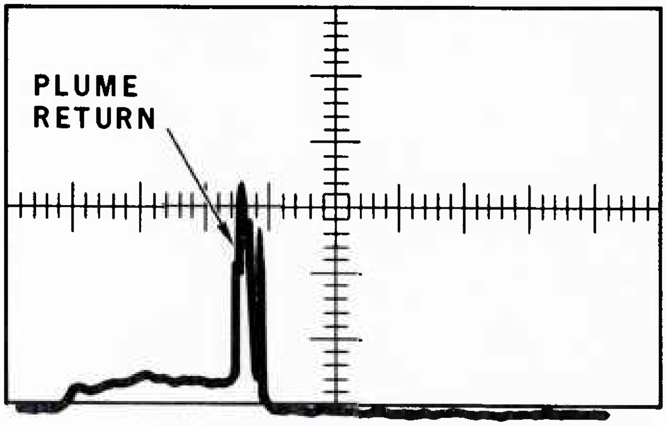

Figure 2. Lidar return from sea spray plume

A composite of the plume widths measured on three different days when the wind velocities were 0.5, 1.0, and 2.3m sec^{-1} is shown in Figure 3. The solid horizontal bars in the isometric view represent the laser photometer line of sight; the vertical tick marks represent measured plume widths. There was no correlation between wind velocity and plume widths: measurements on different days are therefore intermixed with no discernible order. The lower line of sight was 0.5m above the water; the upper bar shown at the 94m and 141m ranges is for the beam height of 3.0m.

The dotted lines outline the plume shape predicted by application of Sutton's (1953) turbulent diffusion theory. The particle concentration χ is given by

$$\chi(x, y, z) = \frac{2Q}{\pi C_y C_z u x^{2-n}} \exp\left[-x^{n-2}\left(\frac{y^2}{C_y^2} + \frac{z^2}{C_z^2}\right)\right] \qquad (1)$$

where

Q = the rate of particle production,

u = the mean wind velocity along the x axis,

C_y and C_z = the horizontal and vertical diffusion coefficients, and

n = a constant, of value 0.25.

The plotted plume boundary is defined, where

$$\chi(x, y, z) = \frac{\chi}{10}(x, 0, 0) \qquad (2)$$

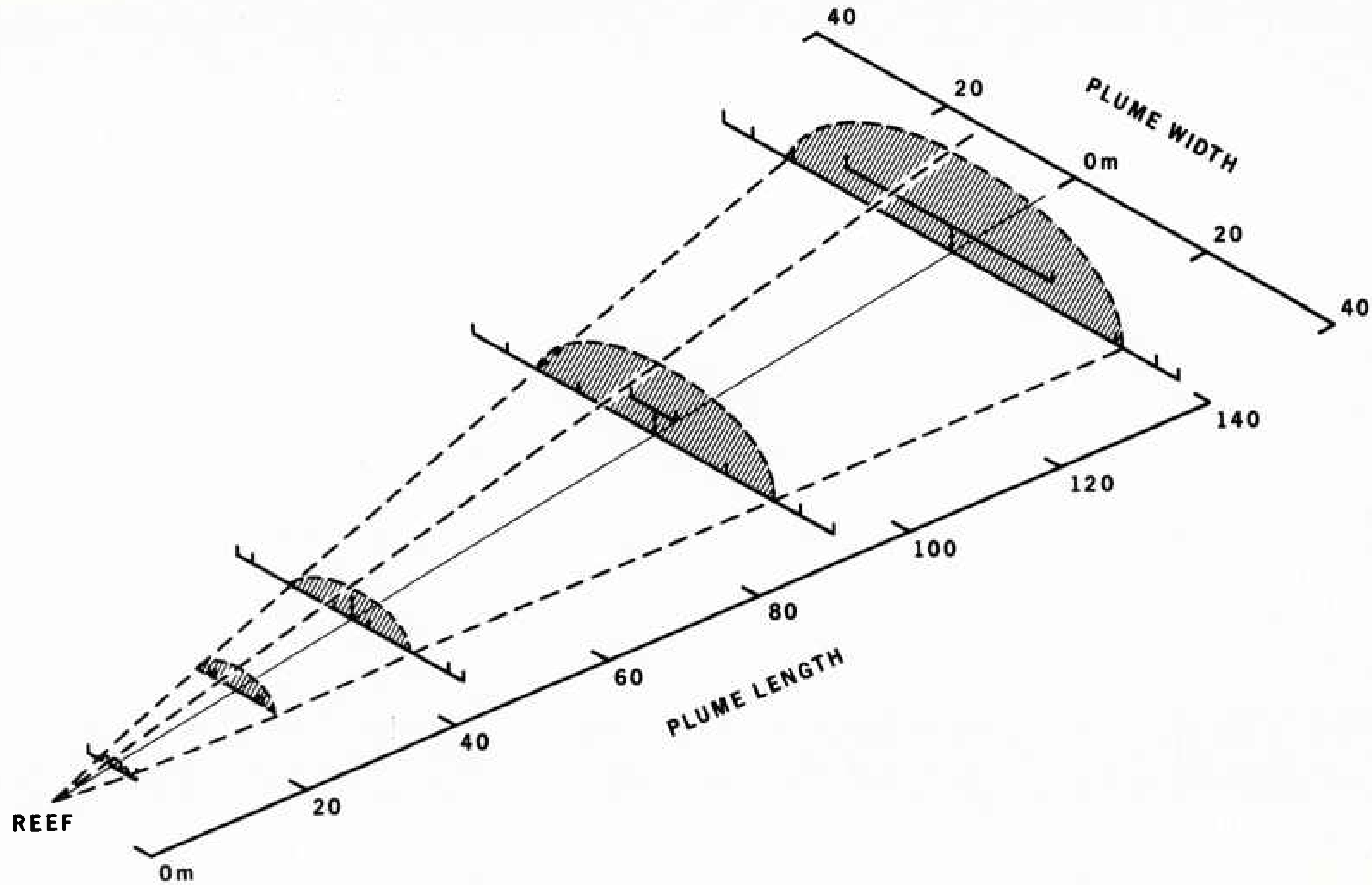

Figure 3. Calculated and measured dimensions of sea spray plumes

and the lidar measured boundary is similarly where the returned scattered light has 0.10 the radiance of the return from the center of the plume. The cross-hatched vertical sections are in the same plane in which the laser probes were made and indicate that in general the width of the plume was somewhat greater and the vertical height somewhat less than would be predicted on the basis of diffusion coefficients found by Sutton. Sutton's values are for diffusion over smooth, level, downland terrain, or $C_y = 0.4 \text{ cm}^{1/8}$ and $C_z = 0.2 \text{ cm}^{1/8}$.

Since each sampling point represents the outer plume edge obtained from three probes with the laser, it might be expected that the lidar-measured widths would be somewhat more narrow, because of the limited statistics, than the time-mean prediction of the diffusion equation. However, the general agreement for the plume widths for the three days plotted indicates that a sufficient statistical sample was made to give a good approximation to the time-mean plume width.

On all three days, the water temperature was 6°C lower than the air temperature at the lidar site, where the elevation is 30m. Such a strong thermal inversion would tend to limit plume development in the vertical direction, as discussed by Inoue (1959). The plumes showed no meandering characteristics which might explain the greater-than-predicted width, but such meandering would not be expected in the stable surface layer. Woodcock and Wyman (1947) have shown that convection in an unstable layer will cause a smoke plume to develop a sinuous pattern, but such conditions were not present during this investigation. The measured plume dimensions

seem to be best described by diffusion coefficients $C_y = 0.55\ \mathrm{cm}^{1/8}$ and $C_z = 0.1\ \mathrm{cm}^{1/8}$.

An advantage in studying the water droplet spray plume instead of its smoke plume analog is that the thermodynamics and mechanics of the plume are measured in the natural state and not modified by differences in source temperature, latent heat of evaporation, and particle size. Indeed, the rather large diameter of some of the spray particles further explains the limited vertical development of the plume, as has been discussed by Yudine (1959). Evaporation in the plume would strengthen the existing inversion to further limit vertical growth; and these two mechanisms -- large droplet fallout, and evaporative cooling -- would be operative in the tropics as well, and would not be discovered by smoke plume investigation.

HOLOGRAPHIC MEASUREMENT OF SPRAY PARTICLE SIZES

Methods for reconstructing the images of small water droplets have been described by Thompson, Ward, and Zinky (1967). Whereas most hologram techniques have been accomplished in the laboratory, or within specially constructed cameras, the technique proved feasible in this study involves replacing the lens of a conventional 35mm camera with an interference filter with a bandwidth of 1.0nm centered at the ruby wavelength of 694nm. Field tests showed that there was sufficient laser irradiance at a range of 500m to produce a photographic negative of density 1.5 on Eastman Kodak emulsion SO-243, even with a No. 2 neutral density filter placed in front of the interference filter. This combination of filters allowed opening

the shutter for two seconds without fogging the film from ambient daylight radiance. With the laser located on the bluff site and the camera with filters located downwind of the reef, it was necessary only to aim the laser beam at the camera and synchronize shutter openings with laser firings to record holograms of the particles drifting in front of the camera.

Laboratory tests had indicated that even without laser spatial filtering, 100μ diameter particles could be recorded at distances up to 20 cm from the camera, which is equivalent to a sample depth of field for particles with diameter d of $14d^2/\lambda$.

To record holograms of the large particles thrown up by the reef, the camera was positioned on rocks that are accessible at low tide. The camera in its waterproof plastic enclosure is shown in Figure 4. To record holograms of the spray particles after they have traveled downwind, the camera had to be removed some distance from the rocks or placed on shore. In the latter case, it was necessary that there be an absence of breaking waves on the beach when the exposure was made.

A reconstruction of spray droplets is shown in Figure 5, where, for clarity, the droplet images have been outlined with a white circle. It is easy to distinguish droplet images from the confusing background pattern of interference fringes when the reconstruction is examined with a traveling microscope in the laboratory. The particles then come into focus very sharply at a location relative to the hologram film plane corresponding to their actual position when photographed. This is true because no lenses were used on

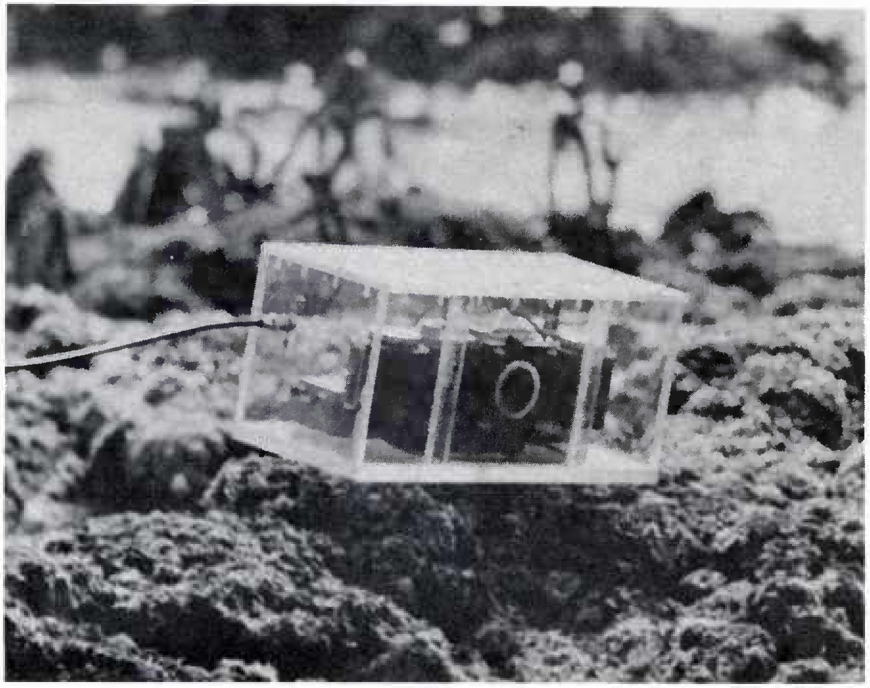

Figure 4. Hologram camera at Reef Point

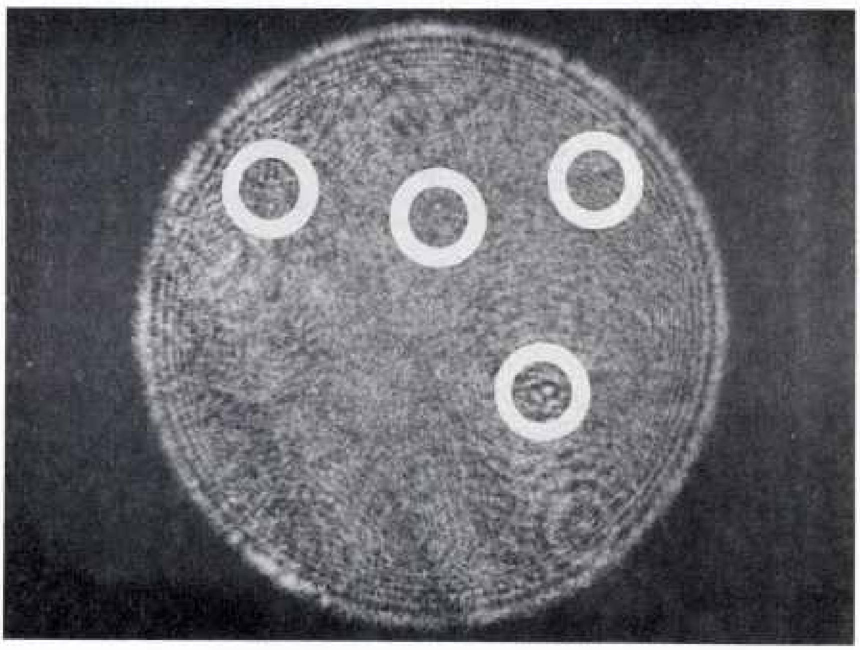

Figure 5. Holographic reconstruction of spray particles

the hologram camera and the reconstructing beam was collimated, as was the recording beam. An insufficient number of successful holograms were recorded to provide good analyses of the droplet size distribution, and it would be desirable to improve the laser coherence length before attempting such a study so as not to discriminate against the smaller-size droplets. With the present arrangement, one-micron droplets could be imaged over only a fraction of a millimeter depth of field.

CONCLUSIONS

The pulsed ruby lidar has been shown to be capable of measuring the width of spindrift plumes at distances extending to several hundred meters from a point source of white water. Under the stable thermal conditions of the measurements, the plume height was significantly less than that found for smoke under conditions of neutral stability, while plume width was somewhat greater. Plume dimensions were found to be independent of wind speed.

The lidar transmitter can also serve as a source for recording holograms of the spray particles as they blow past a suitable camera. The hologram camera has the potential for a much greater depth of field than direct photomicrography of spray particles and in addition allows a three-dimensional reconstruction of the particles for more convenient study in the laboratory. Although these feasibility experiments were conducted in the temperate region, similar data gathered under tropical conditions would be of greater meteorological significance. Studies of spray plumes in the tropics may provide further insight into the source of giant condensation nuclei, which are believed to be so important in explaining warm cloud rain (Riehl, 1954).

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